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The Petrogenesis of the Colorado Plateau Laccoliths and Their Relationship to Regional Magmatism

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ABSTRACT

The petrogenetic processes that formed the Henry Mountains, Utah, may be the same as those responsible for other laccolithic intrusions in the Colorado Plateau, specifically the La Sal and Abajo Mountains. Each range consists of small separate intrusive centers where magma was emplaced into Phanerozoic sediments at shallow crustal levels. Two major rock suites, plagioclase-hornblende porphyry (95 volume percent) and syenite porphyry (5 volume percent) exist in both the Henry and La Sal Mountains, whereas plagioclase-hornblende porphyry alone is found in the Abajo Mountains. Plagioclase-hornblende porphyry evolved from mantle-derived magma, which was ponded in the deep crust and assimilated amphibolite crust during open-system differentiation before being emplaced at shallow crustal levels. Plagioclase-hornblende porphyry also shows isotopic provinciality at each intrusive center, which may, in part, reflect the isotopic diversity of the basement rocks.

Geochemically, the laccoliths and contemporaneous volcanic rocks outside the plateau appear to have strong affinities to arc rocks, although their volume is much less than that of a typical volcanic arc. We contend that the laccoliths are part of an east-west-oriented magmatic belt, itself a portion of a larger mid-Tertiary magmatic system in western North America, and that the minor volume of the laccoliths reflects the inability of large volumes of magma to penetrate the thick, strong, stable crust of the Colorado Plateau.

INTRODUCTION

The laccolithic intrusions of the Henry, La Sal, and Abajo Mountains of southwest Utah (fig. 1) represent much of the igneous activity of the Colorado Plateau interior during mid-Tertiary time. Understanding the origin of the laccoliths will help clarify the fundamental differences in contemporaneous magmatism on and off the plateau, crust-mantle dynamics involved in the formation of the magmas, and regional tectonomagmatic processes.

We review existing data and present new data for all three of the laccolithic ranges (fig. 1), and contemporaneous rocks in adjacent regions of the Western United States to address the following topics:

1. We compare the geochemistry of the rocks from all three mountain ranges in order to assess their differences, their similarities, and their possible tectonic affiliation.

2. We outline the petrogenesis of the Henry Mountains laccoliths, which we propose as a model system to illustrate the interactions between mantle-derived melts and continental crust in the Colorado Plateau. A detailed study is given in Nelson and Davidson (1993).

3. We consider the regional relationships of the laccoliths to roughly contemporaneous and similarly evolved volcanic rocks in the vicinity of the Colorado Plateau in order to evaluate the origins of mid-Tertiary magmatism.

REGIONAL GEOLOGIC SETTING

Deformational and magmatic events have left the Colorado Plateau interior relatively unaffected during the entire Phanerozoic Eon (Allmendinger and others, 1987). However, the Colorado Plateau (fig. 1) is bounded by areas of intense Mesozoic and Cenozoic deformation and magmatism. Cretaceous to Eocene Laramide shortening may have been the result of shallow or flat subduction (Bird, 1988; Hamilton, 1988) and an accompanying magmatic lull in the region of the laccoliths and farther west (Armstrong and Ward, 1991). Mid-Tertiary andesitic to dacitic volcanism in the Reno-Marysvale, San Juan, and Mogollon-Datil belts produced great volumes (≈$5x10^5$ km^3; Johnson, 1991) of ignimbrite and similar rocks, whereas contemporaneous (middle to late Oligocene) magmatism in the Henry, La Sal, and Abajo

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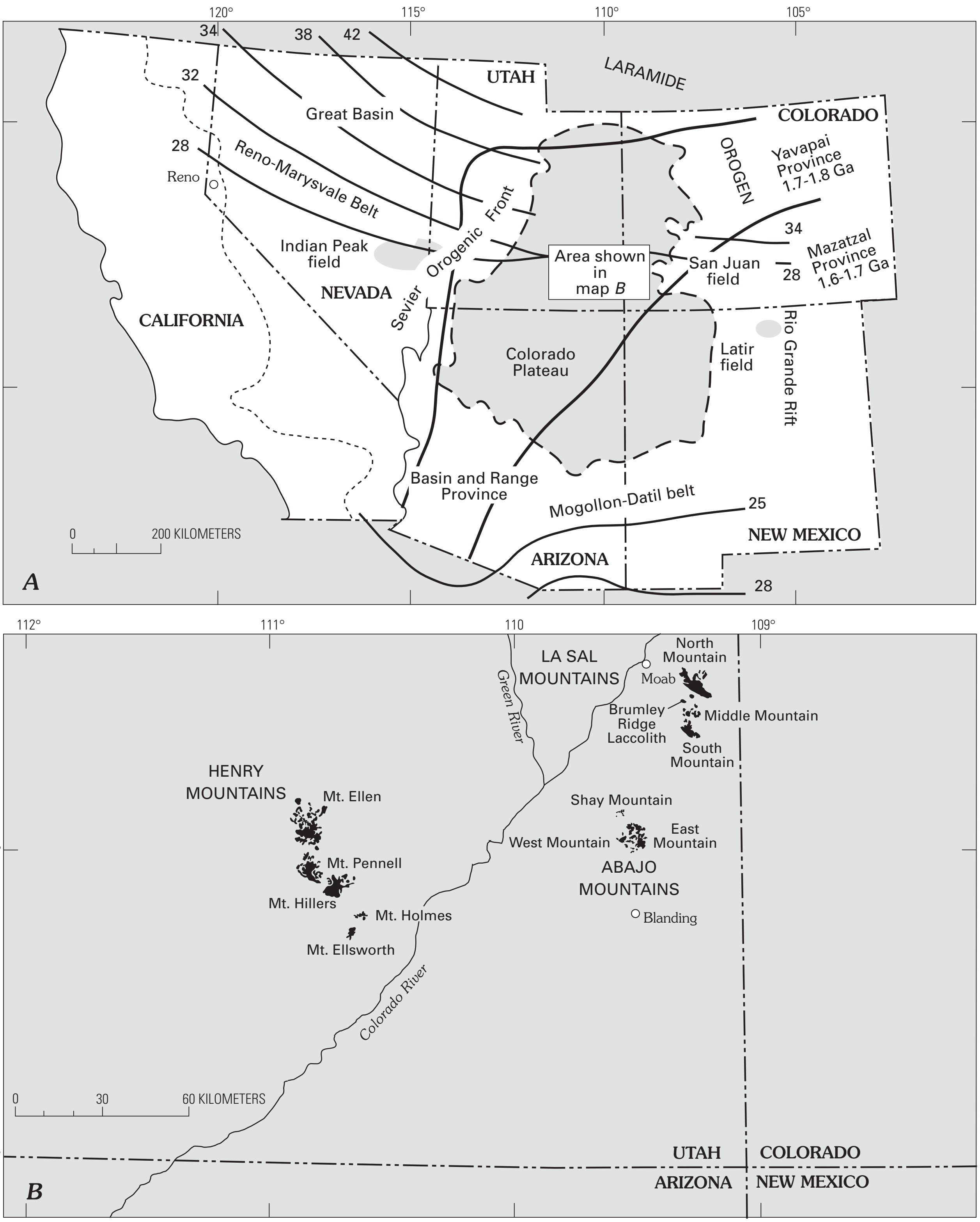

Figure 1. Locations of the Henry, La Sal, and Abajo Mountains, the Colorado Plateau, basement terrane boundaries, and other geographic and tectonomagmatic features of interest. *A*, General setting of the Southwestern United States: Numbers labeling hachured contours show the age (in millions of years) of the onset of mid-Tertiary magmatism as it swept through the Cordillera from the north and from the south (adapted from Cross and Pilger, 1978; Burke and McKee, 1979; and Glazner and Bartley, 1984). Proterozoic basement terrane boundaries from Bowring and Karlstrom (1990). *B*, Detail of the Henry, La Sal, and Abajo Mountains in the central part of the Colorado Plateau.

Mountains was volumetrically minor (69, 50, and 20 km^3, respectively) (Hunt, 1953; 1958; Witkind, 1964). The laccoliths may have been part of a large east-west-oriented late Oligocene magmatic belt extending from Reno, Nev., to the San Juan field in Colorado (Best, 1988; Sullivan and others, 1991; Nelson and others, 1992). This activity was followed by late Cenozoic (<17 Ma) basaltic magmatism around the margins of the Colorado Plateau. Crustal uplift and extension of terranes bordering the Colorado Plateau on the east (Rio Grande Rift) and on the west and south (Basin and Range province) were synchronous with the late Cenozoic volcanism. However, the interior of the Colorado Plateau has had little extension although it has been uplifted in Cenozoic time at rates exceeding those of the Basin and Range province (Lucchitta, 1979). To summarize, crustal deformation and magmatism in the Colorado Plateau has not been as intense as elsewhere in the Cordillera. The structural and rheological characteristics of the plateau may have inhibited large-scale upper-crustal magmatism and deformation.

COLORADO PLATEAU STRUCTURE, GEOPHYSICS, AND COMPOSITION

Geophysical data indicate that the Colorado Plateau is underlain by thick (45–50 km) stable crust (Thompson and Zoback, 1979; Allmendinger and others, 1986, 1987; and Beghoul and Barazangi, 1989) and is covered by a ≈6-km veneer of Late Proterozoic to Tertiary sedimentary rocks. Basement terranes range from about 1.6 to 1.9 Ga in age (Bennett and DePaolo, 1987; Karlstrom and others, 1987; Bowring and Karlstrom, 1990). Crystalline rocks beneath the laccolithic ranges formed a terrane termed the Yavapai province (fig. 1) (Condie, 1982; Karlstrom and others, 1987; Bowring and Karlstrom, 1990) along an east-northeast-trending convergent margin.

Some of the exposed Proterozoic basement rock to the east of the Colorado Plateau consists of metabasalt and other meta-igneous rocks (Knoper and Condie, 1988; Boardman and Condie, 1986), with mafic rocks making up as much as 80 percent of the assemblage in places (Robertson and Condie, 1989). The orientation of Proterozoic terrane boundaries and structural grain (fig. 1) indicates that the same mafic lithologies may form the basement to much of the Colorado Plateau. However, in New Mexico, much of the Proterozoic basement consists of granitoid rocks exposed in uplifts flanking the Rio Grande Rift (see Condie, 1978, for instance); therefore, much of the Mazatzal province (fig. 1) could be composed of silicic crust. Because quartz-rich crust is more easily strained than quartz-poor crust, one would expect deformation to be preferentially concentrated in quartz-rich regions during regional deformation. Thus, the lack of exposures of Proterozoic basement rock in the Colorado Plateau not only mask direct evidence of its composition, but could reflect a relatively mafic bulk composition and physical properties that distributed strain into surrounding terranes. Lower crustal P_n velocities of 6.8 km/s or greater in the Colorado Plateau (Smith and others, 1989; Wolf and Cipar, 1993) are appropriate for mafic rocks (Fountain and Christiansen, 1989). Velocities of 6.5–6.7 km/s or lower in the adjacent Basin and Range province (Smith and others, 1989; Wolf and Cipar, 1993) are more consistent with intermediate to silicic compositions (Fountain and Christiansen, 1989).

Some direct evidence indicates that the plateau is composed of mafic crust. Amphibolite inclusions, ranging from 1 to about 20 cm in diameter, are present in all intrusions and locally compose 1 percent of the laccoliths. They are probably from the Proterozoic Yavapai basement. Most are xenoliths of amphibolite-facies metabasalt, though some consist of hornblende gabbro (textural distinction). A statistical study of 200 randomly collected xenoliths from the Henry and La Sal Mountains showed that >95 percent of them were mafic (Hunt, 1953; 1958). McGetchin and Silver (1972) reported that >65 percent of crustal xenoliths in the Moses Rock dike, a mid-Tertiary diatreme in the Four Corners region of the Colorado Plateau, are basaltic. They estimated an average anhydrous composition for the crystalline portion of the plateau's crust that is surprisingly mafic (54 percent SiO_2, 8 percent MgO).

FIELD RELATIONS

The Henry, La Sal, and Abajo Mountains are cored by hypabyssal intrusions, with separate intrusive centers (5, 3, and 2, respectively) that were emplaced as multiple laccoliths, invading Mesozoic and upper Paleozoic sedimentary rocks. Structurally, individual mountains represent discrete intrusive loci composed of a central laccolith with radial sills and laccoliths and intervening sedimentary screens. Jackson and Pollard (1988) estimated the maximum depth of intrusion at 3 to 4 km (≈1 kbar) on the basis of the laccoliths' position within regional stratigraphic sequences. However, magmatic amphibole would be unstable at pressures less than 1 kbar, and yet breakdown textures are rare in the amphibole of the laccoliths. Thus the maximum intrusion depth given by Jackson and Pollard (1988) is close to the minimum depth based on petrographic considerations. One exception may be the middle La Sal Mountains, which show some breakdown of hornblende and are emplaced at a higher level in the stratigraphic section (Hunt, 1958; Michael Ross, Utah Geological Survey, oral commun., 1992).

The dominant rock type (95 volume percent) of the intrusions is plagioclase-hornblende porphyry (termed "diorite" by Hunt, 1953, 1958; Engel, 1959; Witkind, 1964; Irwin, 1973; and Hunt, 1988). It typically consists of 20–25 volume percent phenocrysts of plagioclase and about 10 volume percent hornblende in a fine-grained groundmass. The plagioclase is euhedral to subhedral, 0.5 to 5 mm in cross section, ranges from An_{30} to An_{45}, and shows complex zoning patterns. The hornblende is also euhedral to subhedral and is generally <1 mm in length, but can be as long as 5 mm. The remainder of the rock generally consists of an equigranular aphanitic groundmass of plagioclase, quartz, and alkali feldspar with trace quantities of apatite and sphene. Some plagioclase-hornblende porphyry, especially in the La Sal Mountains, contains clinopyroxene in subequal quantities to hornblende. At the Henry and La Sal Mountains, small volumes (5 volume percent) of fine-grained nepheline- to quartz-normative Na-rich syenite and rhyolite porphyries were emplaced as small stocks, laccoliths, and dikes that crosscut the plagioclase-hornblende porphyry. These rocks are described in detail in Nelson (1991) and are petrographically and geochemically diverse, especially in the La Sal Mountains. Syenite porphyry is restricted to Mount Pennell in the Henry Mountains and to North Mountain and the Brumley Ridge laccolith in the La Sal Mountains; it is apparently absent in the Abajo Mountains.

GEOCHEMICAL CHARACTERISTICS OF THE LACCOLITHS

In terms of major-element chemistry, the porphyries of the Abajo Mountains show considerable similarity to the plagioclase-hornblende porphyry of the Henry Mountains as determined from a small sample set (fig. 2*A*, *B*; table 1). The remaining compositional range shown in figure 2B represents data from Witkind (1964), who attributes at least some of the variation in total alkali contents to hydrothermal alteration. The trace-element systematics of the Abajo laccoliths are virtually identical to those of the plagioclase-hornblende porphyry of the Henry Mountains, which are summarized in figure 3*A*. Overall, the laccoliths have trace-element patterns similar to those of calc-alkaline basalt, although they have higher absolute elemental abundances except for titanium and phosphorus (fig. 3*B*). Fresh porphyry from the Abajo Mountains is, in general, somewhat more radiogenic than the plagioclase-hornblende porphyry of the Henry Mountains in terms of strontium isotopes (fig. 4). Given the similar age, tectonic and structural setting, and geochemical characteristics of the Henry and Abajo Mountains, it is our opinion that they reflect nearly identical igneous histories.

Despite locally pervasive alteration, the porphyries of the La Sal Mountains have primary geochemical differences that distinguish them from the Henry and Abajo Mountains. These rocks are also divided into a plagioclase-hornblende porphyry suite and a syenite-alkaline rhyolite suite (fig. 2*C*) on the basis of major-element criteria and petrographic characteristics. The plagioclase-hornblende porphyry is more alkali-rich than rocks of the Henry and Abajo Mountains, and ranges from 60 to 63 percent SiO_2. In fact some of the plagioclase-hornblende porphyry is sufficiently enriched in alkalies that it is nepheline-normative.

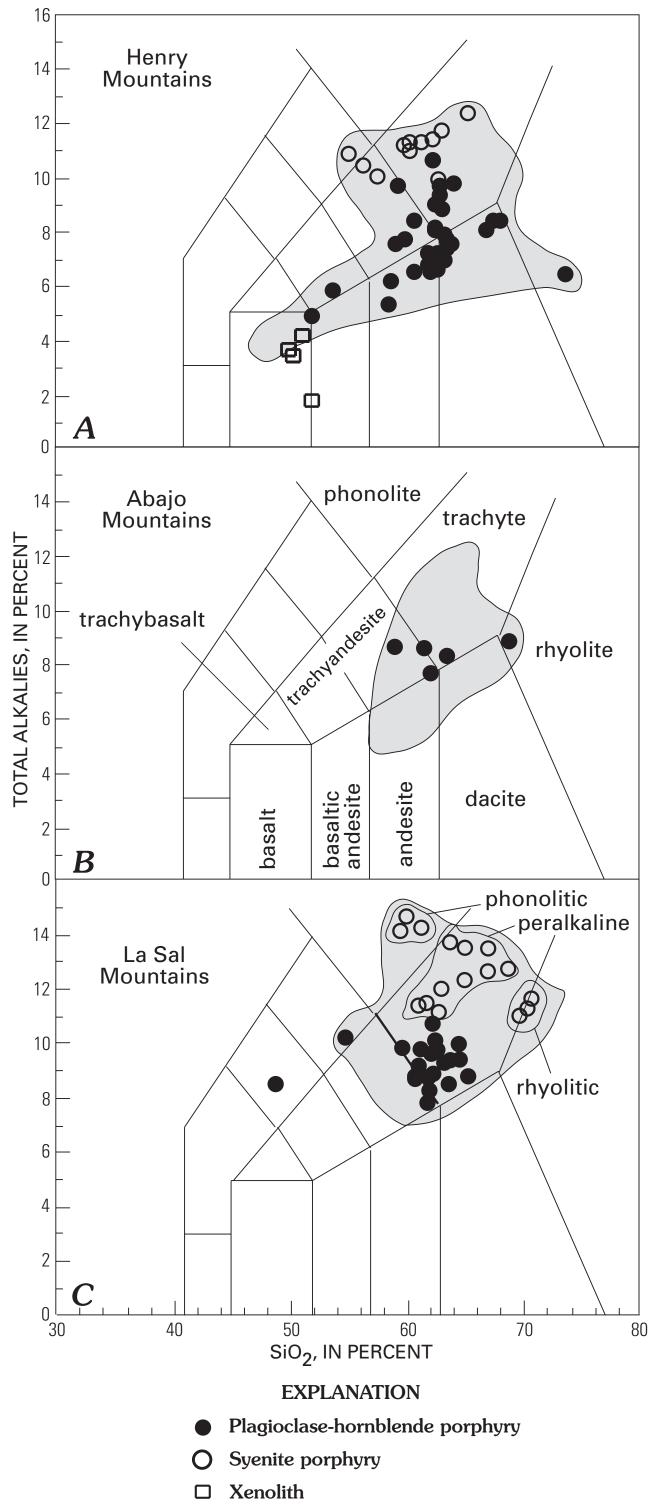

Figure 2. Total alkalies versus silica (Le Bas and others, 1986) for the Henry (*A*), Abajo (*B*), and La Sal (*C*) Mountains, Utah. Shaded fields represent the reported ranges of compositions from data in Nelson (1991), Hunt (1953, 1958), Engel (1959), Hunt (1988), and Witkind (1964).

Syenitic to rhyolitic rocks of the La Sal Mountains are divided into subtypes on the basis of petrographic and

Table 1. Representative geochemical data and sample localities for rocks of the La Sal and Abajo Mountains, Utah.

[Analytical details are the same as reported by Nelson and Davidson (1993). LOI, loss on ignition; n.d., not determined]

	Syenite porphyry samples							Plagioclase-hornblende porphyry of La Sal Mountains			
Sample No.	CSTV–3KRS	MW-2	MW–6	MW–18	MW–17	LAS–1KRS	TUK–1	MW–3	MW–13	MW–14	WLKE–1
North latitude	109°16'34"	109°14'46"	109°14'48"	109°13'31"	109°13'29"	109°17'05"	109°15'57"	109°14'47"	109°14'05"	109°12'19"	109°15'55"
West longitude	38°32'56"	38°32'19"	38°32'17"	38°31'19"	38°31'19"	38°28'57"	38°27'23"	38°32'36"	38°32'34"	38°30'08"	38°30'21"
Major oxides in percent											
SiO_2	61.89	67.17	71.03	69.82	60.32	59.62	61.43	64.55	62.39	62.86	61.98
TiO_2	.55	.27	.20	.08	.16	.17	.15	.42	.52	.46	.50
Al_2O_3	16.89	16.86	12.55	15.01	19.54	19.08	19.70	17.24	16.90	17.39	17.76
FeO	3.75	2.06	2.87	1.14	1.82	1.71	1.67	3.71	4.03	3.77	4.01
MgO	1.01	.41	.23	.09	.10	.13	.16	1.23	1.47	.94	1.17
MnO	.14	.14	.14	.13	.13	.14	.14	.14	.14	.13	.16
CaO	2.78	.92	.41	.35	1.17	1.22	1.10	3.19	3.46	2.95	4.11
Na_2O	6.93	7.26	3.42	6.91	9.33	8.94	9.07	6.78	7.52	6.54	6.94
K_2O	4.68	5.56	8.29	4.28	5.46	5.34	5.33	2.91	3.42	3.30	2.99
P_2O_5	.19	.08	.08	.02	.03	.02	.02	.18	.24	.20	.21
LOI	1.18	.29	.06	1.38	1.09	3.40	1.60	.00	.59	.79	1.07
Total	99.80	100.94	99.20	99.18	99.12	99.75	100.35	100.17	100.44	99.12	100.69
Trace elements in parts per million (analyzed by X-ray fluorescence, except as noted)[1]											
Pb	7	14	13	82	34	36	35	10	13	10	26
Rb	128	135	246	69	149	138	135	49	80	83	76
Ba	772	556	183	724	211	424	361	757	969	719	837
Th	23	[2] 30.0	[2] 165.6	15	25	21	[2] 19.4	[2] 5.2	8	7	[2] 8.9
U	9	[2] 6.9	[2] 31.6	4	13	12	[2] 10.5	[2] 2.2	1	4	[2] 3.3
Nb	16	14	18	21	13	15	14	11	12	10	15
La	57	[2] 16.5	[2] 33.5	19	36	43	[2] 35.4	[2] 30.0	43	26	[2] 43.5
Sr	737	910	242	165	916	1416	1207	1043	1027	1197	1562
Zr	268	279	540	136	265	230	276	240	227	174	286
Y	31	12	18	7	10	12	12	21	21	18	21
Ni	4	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	2	2	3	1
Cr	10	7	7	5	5	8	7	8	8	6	8
Isotopic analyses (Pb ratios corrected for fractionation)											
$^{87}Sr/^{86}Sr \pm 2\sigma$	0.704938 ±0.000028	0.705061 ±0.000011	0.704806 ±0.000011	0.704574 ±0.000013	0.704293 ±0.000013	0.704226 ±0.000010	0.704325 ±0.000010	0.704174 ±0.000011	n.d.	0.704262 ±0.000010	0.704199 ±0.000010
$^{143}Nd/^{144}Nd \pm 2\sigma$	0.512525 ±0.000010	0.512427 ±0.000008	0.512450 ±0.000010	0.512443 ±0.000010	0.512489 ±0.000009	0.512490 ±0.000016	n.d.	n.d.	n.d.	0.512367 ±0.000008	0.512352 ±0.000016
εNd	−2.21	−4.12	−3.67	−3.80	−2.90	−2.89	n.d.	n.d.	n.d.	−5.29	−5.58
$^{206}Pb/^{204}Pb$	n.d.	19.411	n.d.	18.685	18.781	18.856	n.d.	n.d.	n.d.	18.574	n.d.
$^{207}Pb/^{204}Pb$	n.d.	15.650	n.d.	15.585	15.614	15.627	n.d.	n.d.	n.d.	15.582	n.d.
$^{208}Pb/^{204}Pb$	n.d.	38.790	n.d.	38.261	38.303	38.389	n.d.	n.d.	n.d.	37.971	n.d.

	Plagioclase-hornblende porphyry of La Sal Mountains						Plagioclase-hornblende porphyry of Abajo Mountains				
Sample No.	WLKE-3	WLKE-4	TUK-2	PEAL-2	TUK-5	LASE-1	MONT-1KRS	MONT-2KRS	MONT-3KRS	MONT-4KRS	LJN-1KRS
North latitude	109°21'44"	109°15'27"	109°16'15"	109°14'15"	109°15'10"	103°13'23"	109°27'09"	109°29'58"	109°27'09"	109°28'33"	109°30'12"
West longitude	38°36'46"	38°31'00"	38°31'36"	38°26'12"	38°24'27"	38°22'00"	37°48'11"	37°50'42"	37°51'08"	37°51'08"	37°49'34"
Major oxides in percent											
SiO_2	65.50	64.70	61.60	61.97	61.08	61.27	63.52	61.57	59.17	62.23	68.99
TiO_2	.40	.30	.49	.46	.58	.55	.43	.47	.54	.48	.20
Al_2O_3	17.06	16.06	17.88	17.88	17.70	17.50	17.47	17.62	17.12	17.51	15.38
FeO	2.33	2.90	3.81	3.98	5.06	4.68	3.70	3.82	4.48	3.92	1.75
MgO	1.42	.91	.99	.95	1.51	1.32	1.12	1.03	1.44	1.16	.52
MnO	.14	.13	.14	.10	.13	.13	.14	.16	.15	.14	.14
CaO	4.83	2.34	4.61	4.48	5.07	3.90	5.12	5.51	5.63	4.39	2.30
Na_2O	8.11	6.77	7.36	6.14	5.18	6.14	5.88	6.07	6.26	5.48	5.61
K_2O	.81	3.27	2.48	2.67	3.65	2.75	2.50	2.57	2.44	2.24	3.42
P_2O_5	.19	.15	.19	.20	.28	.27	.17	.17	.22	.18	.07
LOI	1.51	.63	1.31	.99	.67	1.00	.00	.64	4.30	.00	1.60
Total	102.11	98.01	100.67	99.61	100.90	99.50	100.05	99.63	101.75	97.73	99.98
Trace elements in parts per million (analyzed by X-ray fluorescence, except as noted) [1]											
Pb	7	8	13	13	13	7	16	15	13	11	39
Rb	20	58	44	54	92	41	42	51	45	42	64
Ba	274	940	780	773	996	921	767	964	721	724	958
Th	[2] 3.1	3	[2] 8.6	6	11	9	3	5	4	3	2
U	[2] 1.7	4	[2] 3.9	4	3	2	1	2	1	1	2
Nb	n.d.	10	n.d.	8	8	8	17	16	16	17	14
La	[2] 21.4	17	[2] 41.0	31	51	32	23	35	29	24	13
Sr	925	1035	1728	1393	1287	10004	827	964	864	1011	882
Zr	170	160	284	194	179	191	153	153	143	157	105
Y	14	15	24	24	26	27	30	26	35	30	18
Ni	0	5	1	4	6	4	1	n.d.	2	n.d.	n.d.
Cr	7	9	8	6	6	6	8	8	8	8	7
Isotopic analyses (Pb ratios corrected for fractionation)											
$^{87}Sr/^{86}Sr \pm 2\sigma$	0.703928 ±0.000010	n.d.	0.704426 ±0.000010	0.704443 ±0.000011	0.704810 ±0.000010	n.d.	0.705463 ±0.000010	0.705513 ±0.000010	n.d.	n.d.	0.705976 ±0.000010
$^{143}Nd/^{144}Nd \pm 2\sigma$	n.d.	n.d.	0.512419 ±0.000009	0.512466 ±0.000008	0.512436 ±0.000007	n.d.	0.512333 ±0.000026	0.512353 ±0.000007	n.d.	n.d.	0.512367 ±0.000007
εNd	n.d.	n.d.	–4.27	–3.36	–3.94	n.d.	–5.94	–5.55	n.d.	n.d.	–5.28
$^{206}Pb/^{204}Pb$	n.d.	18.430	n.d.	18.828	18.945	n.d.	18.309	n.d.	n.d.	n.d.	18.601
$^{207}Pb/^{204}Pb$	n.d.	15.557	n.d.	15.584	15.624	n.d.	15.533	n.d.	n.d.	n.d.	15.586
$^{208}Pb/^{204}Pb$	n.d.	37.721	n.d.	38.267	38.378	n.d.	37.772	n.d.	n.d.	n.d.	37.977

[1] X-ray fluorescence determinations below 10 ppm should be considered semiquantitative.
[2] Determined by instrumental neutron activation analysis (INAA).

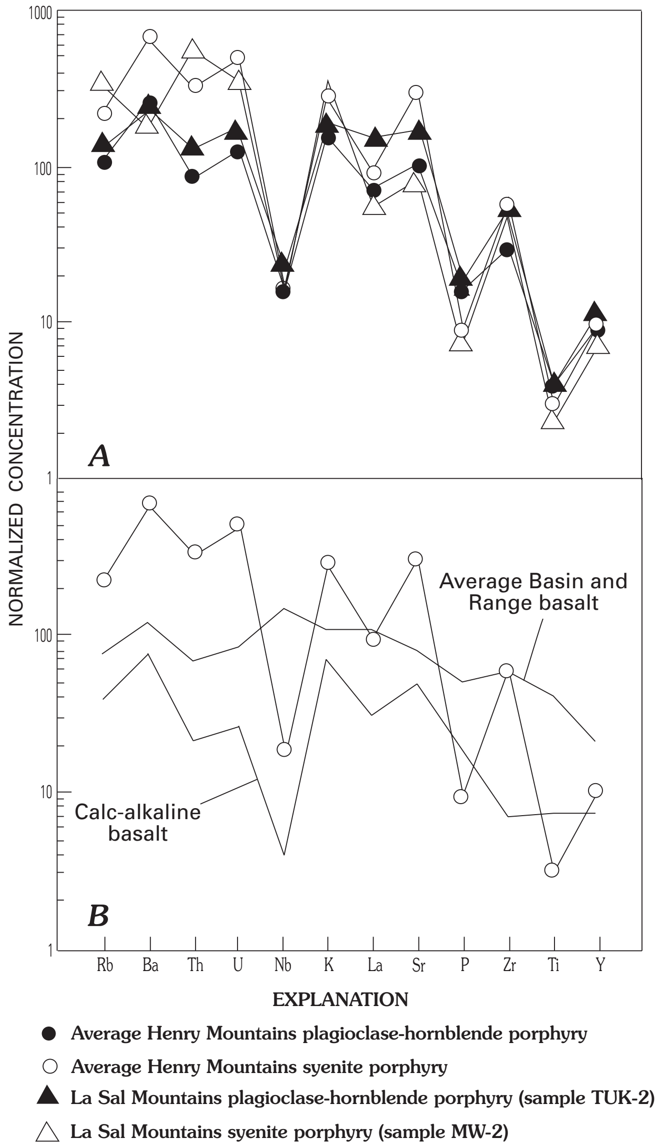

Figure 3. Relative trace-element abundances (normalized to primitive mantle, after Sun, 1980) of plagioclase-hornblende porphyry and syenite porphyry from the Henry and La Sal Mountains, Utah (*A*), compared to those of typical calc-alkaline basalts (Sun, 1980) and intraplate basalts of the Basin and Range province (Ormerod and others, 1988; Fitton and others, 1988) (*B*). Note the similarity of the porphyries to the calc-alkaline basalts and their dissimilarity to the Basin and Range basalts.

geochemical criteria. A small group of phonolitic or feldspathoid- (nosean-) bearing syenite porphyry (fig. 2C) occurs in a large dike at North Mountain and in the Brumley Ridge laccolith (Hunt, 1958) of Middle Mountain. These nosean-bearing rocks are strongly undersaturated (nepheline y nepheline- to quartz-normative and commonly peralkaline (acmite-normative) syenite porphyry, which is richer in silica and poorer in alkalies than the feldspathoid-bearing syenite (fig. 2C). A last group consists of quartz-phyric low-silica peralkaline rhyolite porphyry, which we interpret to be a differentiate of peralkaline syenite.

Trace-element patterns of the porphyries of the La Sal Mountains show some significant deviations from the patterns of the Henry and Abajo Mountains, although there is still a distinct relative depletion in Nb (figs. 3A, 5), suggesting an affinity to orogenic magmatism. $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ are more restricted in the La Sal porphyries (fig. 4).

The lack of trends in the La Sal Mountains major-element data set (fig. 6; table 1) and the distinct geochemical differences relative to the porphyries of the Henry and Abajo Mountains may be the result of some combination of major element mobility during alteration, different magma sources, and different petrogenetic processes. Because of a lack of correlation (fig. 6), the data are not amenable to extensive interpretation, and this lack of correlation extends to trace-element and isotope systematics as well. Therefore, petrogenetic processes in the Henry Mountains must serve as a general model for the La Sal Mountains, despite the geochemical differences.

MAGMA CHEMISTRY AND PETROGENESIS IN THE HENRY MOUNTAINS

Fortunately, the major-element variations in the Henry Mountains are much more orderly and amenable to interpretation than those of the La Sal Mountains (fig. 6). As the syenite porphyry represents <5 percent of the volume of the

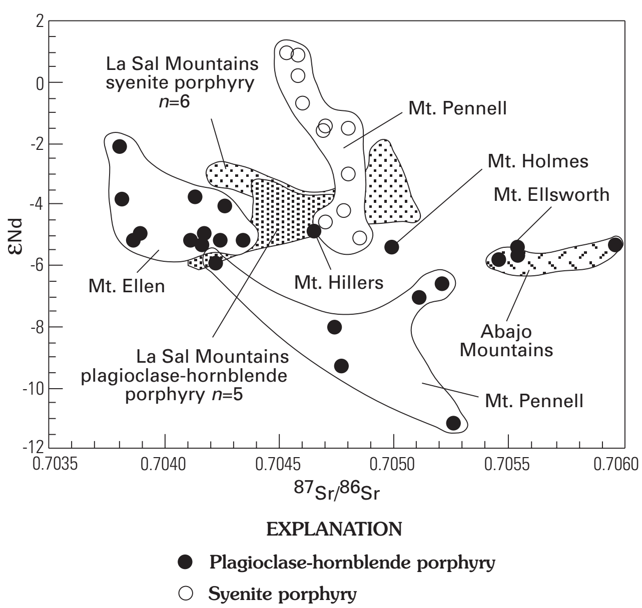

Figure 4. εNd versus $^{87}Sr/^{86}Sr$ in rocks of the Henry, La Sal, and Abajo Mountains, Utah. Note the isotopic provinciality of each of the intrusive centers of the Henry Mountains.

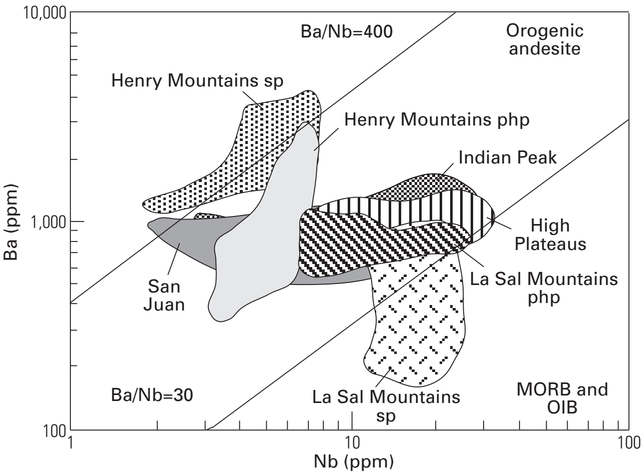

Figure 5. Barium versus niobium in syenite porphyry (sp) and plagioclase-hornblende porphyry (php) of the Henry and La Sal Mountains, Utah, and in contemporaneous magmatic rocks from the High Plateaus of Utah (Mattox, 1991), the San Juan field, Colorado (Colucci and others, 1991; Lipman and others, 1978), and the Indian Peak field, Nevada (Best and others, 1989). All of these show a general affinity to subduction-generated andesites. The field for orogenic andesite and the combined field for MORB (mid-oceanic-ridge basalt) and OIB (oceanic-island basalt) are modified from Gill (1981).

Henry Mountains, we will focus on the origin and evolution of the plagioclase-hornblende porphyry, which, we suggest, will also serve as a model for the evolution of similar rocks in the other ranges. The following review is based on a detailed examination of the petrogenesis of both the syenite and the plagioclase-hornblende porphyry of the Henry Mountains, which can be found in Nelson and Davidson (1993).

Plagioclase-hornblende porphyry for each intrusive center has a distinct range of strontium, neodymium, and lead isotopic compositions. Meta-mafic rocks of the Yavapai and Mazatzal provinces and crustal xenoliths from the laccoliths show extreme variations, which are reflected in the isotopic diversity of the magmas (Nelson and Davidson, 1993; Nelson and DePaolo, 1984). The porphyries at Mount Ellen show systematic, major element, trace element, and isotopic trends that allow the evaluation of petrogenetic processes. εNd is negatively correlated with rubidium among the plagioclase-hornblende porphyries at Mount Ellen, constraining the nature and extent of open-system behavior. AFC (assimilation and fractional crystallization; DePaolo, 1981) models indicate 40–45 percent crystallization and deep crustal magmatic evolution (rate of mass assimilation/mass fractionation (r) = 0.7–0.5; Nelson and Davidson, 1993).

Given the isotopic provinciality of the data set, heterogeneity of the crust, and the dominance of plagioclase-hornblende porphyry with 60–63 percent silica (fig. 2*A*), the following model is proposed. A flux of mantle-derived

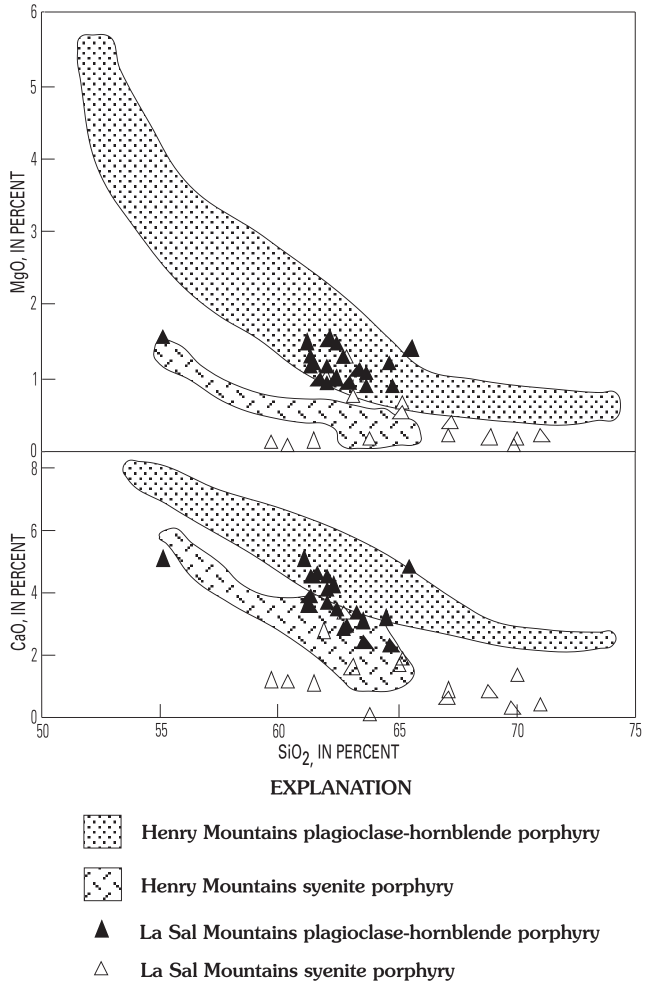

Figure 6. Harker variation diagrams comparing rocks of the Henry Mountains to those of the La Sal Mountains, Utah. The general lack of correlation in major-element data of the La Sal porphyries is also observed in their trace-element and isotope systematics.

magmas impinged upon the base of the crust, and those magmas that penetrated into the crust ponded in deep-crustal magma reservoirs in which there was sufficient recharge or underplating for AFC to proceed with a high rate of mass assimilation to crystallization (r >0.5). Isotopic provinciality is attributed to heterogeneity in the net assimilant at each igneous center or mantle source region. The narrow range of SiO_2 concentrations and the general lack of mafic rocks in most laccoliths suggest that the magmas were able to rise to a shallow crustal level only when a critical density had been reached sufficient to overcome a strength or buoyancy barrier in the crust. Because magmas are so much more compressible than solid rock, the density contrast between magma and wall rock will be much smaller in the lower crust than at the surface, even though the magma is mafic. Based on a model by Herzberg (1987), a basaltic magma at 1,200°C and 10 kbar is only on the order of 0.15 g/cm^3 less dense than solid amphibolite, whereas the density contrast may double to 0.3 g/cm^3 at the surface. At 10 kbar and 850°C, a magma composition representative of the laccoliths (63 percent silica) is much more buoyant, having a density contrast of ≈0.35 g/cm^3. In this light, it may be perfectly reasonable to expect mafic magmas to pond deep in the crust, especially when they are surrounded by high-strength mafic wall rock.

The presence of isotopically primitive mafic rocks (in a relative sense) at Mount Ellen requires the source of the magmas to lie dominantly in the mantle. In addition, the trace-element systematics of both the plagioclase-hornblende porphyry, and especially the syenite porphyry, seem to require that apparent geochemical similarities to arc magmas (Nelson and Davidson, 1993) were probably inherited from the mantle rather than by contamination from continental crust.

REGIONAL TECTONOMAGMATIC CONSIDERATIONS

There is little disagreement that mid-Tertiary magmatism in the laccoliths and other areas of the Western United States, such as the Great Basin and the San Juan field, is fundamentally basaltic. In the rhyolitic magma, however, the primary tie to basaltic magma may be through (1) fractional crystallization accompanied by assimilation of crust or (2) crustal melting due to underplating of basalts. An additional consideration is the mechanism that triggers the influx of magma that drives silicic magmatism. As an example, the flux of basaltic magma might result from subduction, or it may have begun at "passive" hot spots in response to crustal extension, mantle upwelling, and decompression melting. Combining the two end members for the origin of mantle-derived magmas with both end members for the petrogenesis of silicic magmas yields a variety of tectonomagmatic scenarios for their origin. However, we present evidence that suggests that regional magmatism, including the laccoliths, resulted from subduction-related processes, and that the range of observed compositions (basaltic andesite to rhyolite) represents open-system evolution of mantle-derived magmas. In order to resolve differences between the models we review some of the major-element, trace-element, and isotopic characteristics of regional mid-Tertiary (≈32–24 Ma) magmatism together with probable changes in the plate tectonic configuration of the Western United States during that period.

First, the major-element and isotopic characteristics of regional mid-Tertiary silicic magmas are not consistent with a crustal-melting model. In most instances, crustal anatexis ought to produce melts that are either substantially more silica-rich or more quartz-normative than the dacitic-rhyodacitic melts of the large ash-flow sheets of the ignimbrite flareup (Best and others, 1989; Lipman and others, 1978). In the melting of felsic crust, minimum melts (fig. 7)

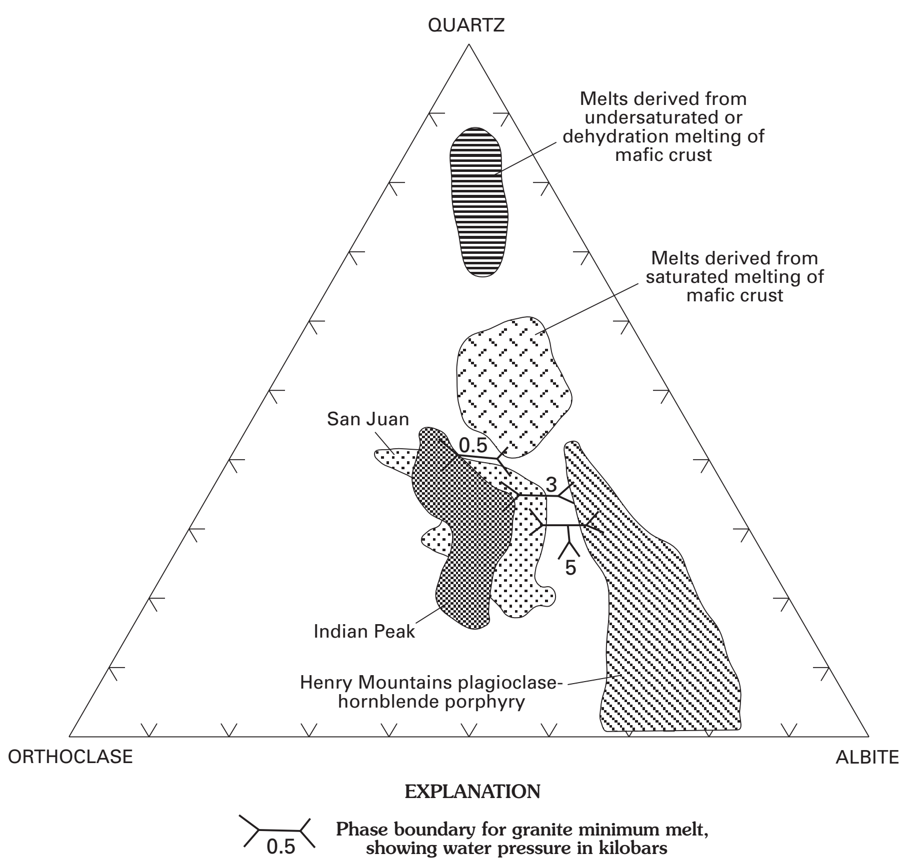

Figure 7. Ternary diagram plotting normative compositions of Henry Mountain laccoliths; of ash-flow sheets of the Indian Peak (Best and others, 1989) and San Juan (Lipman and others, 1978) fields; of melts derived from mafic crust in water-saturated (Helz, 1976), undersaturated (Allen and Boettcher, 1978), and dehydrated (Rushmer, 1991) conditions; and of granite minimum melts (labeled phase boundaries at 0.5, 3, and 5 kbar water pressure). Note that the laccoliths and ash-flow sheets do not correspond well to either type of crustal melt.

ought to predominate, unless the degree of melting is sufficient to exhaust quartz or one of the feldspars. However, few silicic ash-flow sheets have minimum-melt compositions (fig. 7), whereas most are displaced from thermal minima at all pressures. Thus, the dacite to low-silica rhyolites of many mid-Tertiary caldera complexes of the Western United States contain a significant fraction of mafic minerals (Best and others, 1989) and are not minimum melts because they are neither liquids derived from felsic crust, nor sufficiently evolved via fractional crystallization. Also, the plagioclase-hornblende porphyry of the Henry Mountains and the regional ash-flow sheets do not have appropriate compositions to be melts derived from mafic crust (fig. 7), although experimental data suggest that such melts may exhibit a range of compositions depending on the starting material and conditions of melting. Melting of mafic crust (fig. 7) generally produces liquids that are highly quartz normative (tonalites, also containing a significant anorthite component) unless large degrees of melting occur (Helz, 1976, Allen and Boettcher, 1978; Beard and Lofgren, 1991; Rushmer, 1991). In addition, these caldera complexes are surrounded by and intercalated with andesites and basaltic andesites (Best and others, 1989; Lipman and others, 1978). We find no compelling reason to suppose that the silicic ash flows are crustal melts rather than more evolved components of the same mantle-derived system as the andesites.

Based upon an exhaustive review of available isotopic data for the Western Cordillera, Johnson (1991) and Perry and others (1993) concluded that commonly 50 percent or more of the mass of the silicic ash flows originated as mantle-derived basalt that evolved via fractional crystallization or AFC processes. Therefore, we give further consideration to the isotopic character of the laccoliths and related rocks in the region, to assess the relative contributions of crustal and mantle sources (fig. 8). We have calculated ranges of expected isotopic compositions for 1,800-Ma crust that originated from either depleted or undepleted mantle and has evolved from Rb/Sr and Sm/Nd ratios matching those reported by Weaver and Tarney (1984) and Taylor and McLennan (1985) for average continental crust. The purpose of this exercise is not to infer the isotopic composition of the crust that has already been demonstrated to be heterogeneous (Nelson and Davidson, 1993), but to illustrate that relatively mafic rocks (regional basaltic andesites) and silicic rocks (laccoliths and regional ash-flow sheets) may contain a substantial amount of mantle-derived material even if they are contaminated to “crust-like” isotopic compositions.

The Grizzly Peak Tuff (fig. 8) has isotopic characteristics similar to our calculated crustal values. Johnson and Fridrich (1990) note that the primitive end member of this zoned ash-flow sheet is somewhat mafic (57 percent SiO_2), and would have required an unrealistically large degree of melting of mafic crust (≈60 percent) to produce the observed SiO_2 concentration. Such a melt should also have concentrations of other major elements quite different from those of the observed magma. Furthermore, although the lavas of the High Plateaus (fig. 8) also resemble our calculated crust, they are too mafic (50–62 percent SiO_2) to be crustal melts. Clearly, “crustal” isotopic signatures alone may be misleading in assigning crustal anatexis origins even for silicic ignimbrites and laccoliths. The laccoliths lie between mantle and crustal isotopic end members (fig. 8), and the petrogenetic model for the plagioclase-hornblende porphyry described earlier in this paper may represent a link between the two reservoirs.

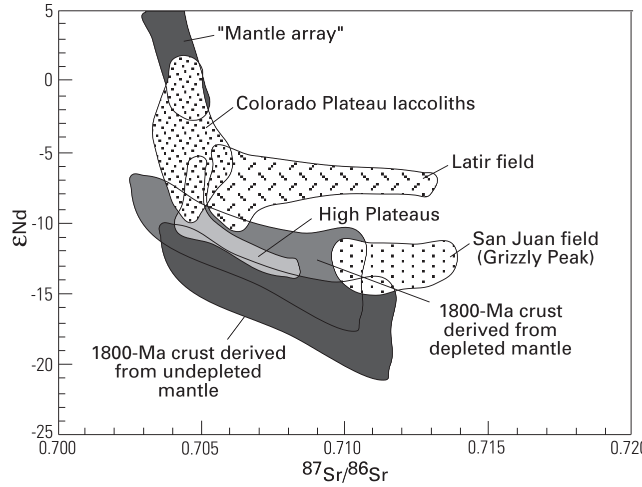

Figure 8. εNd versus $^{87}Sr/^{86}Sr$ in Colorado Plateau laccoliths, in rocks of the High Plateaus of Utah (S.R. Mattox, unpub. data, 1991), and in ignimbrites of the San Juan field, Colorado (Grizzly Peak; Johnson and Fridrich, 1990), and the Latir field, New Mexico (Johnson and others, 1990). Also shown are the hypothetical ranges of 1,800-Ma crust that had initial isotopic ratios derived from depleted and undepleted mantle and has evolved to the Rb/Sr and Sm/Nd ratios of average continental crust reported by Weaver and Tarney (1984) and Taylor and McLennan (1985).

Many studies have suggested that subduction beneath the Western United States was shallow or flat during the Laramide orogeny but then steepened in mid-Tertiary time. (See, for example, Bird 1988; Severinghaus and Atwater, 1990; Armstrong and Ward, 1991; and Best and Christiansen, 1991.) Models of passive extension, however, do not account for the influence of the subducted plate that must have existed beneath the Western United States during mid-Tertiary time. Recent plate-tectonic reconstructions permit the existence of a seismically active subducted slab far inland from the paleo-plate margin—as far east as the San Juan field—as the subduction angle steepened following Laramide compression (fig. 9). Even in the most conservative case, the aseismic extensions of the slab may have contributed to petrogenesis. Therefore, it is reasonable to conclude that subducted oceanic lithosphere could have exerted primary control on the composition, distribution, and timing of magmatism after the Laramide orogeny.

Available data from the High Plateaus (Mattox, 1991), San Juan field (Colucci and others, 1991), Indian Peak

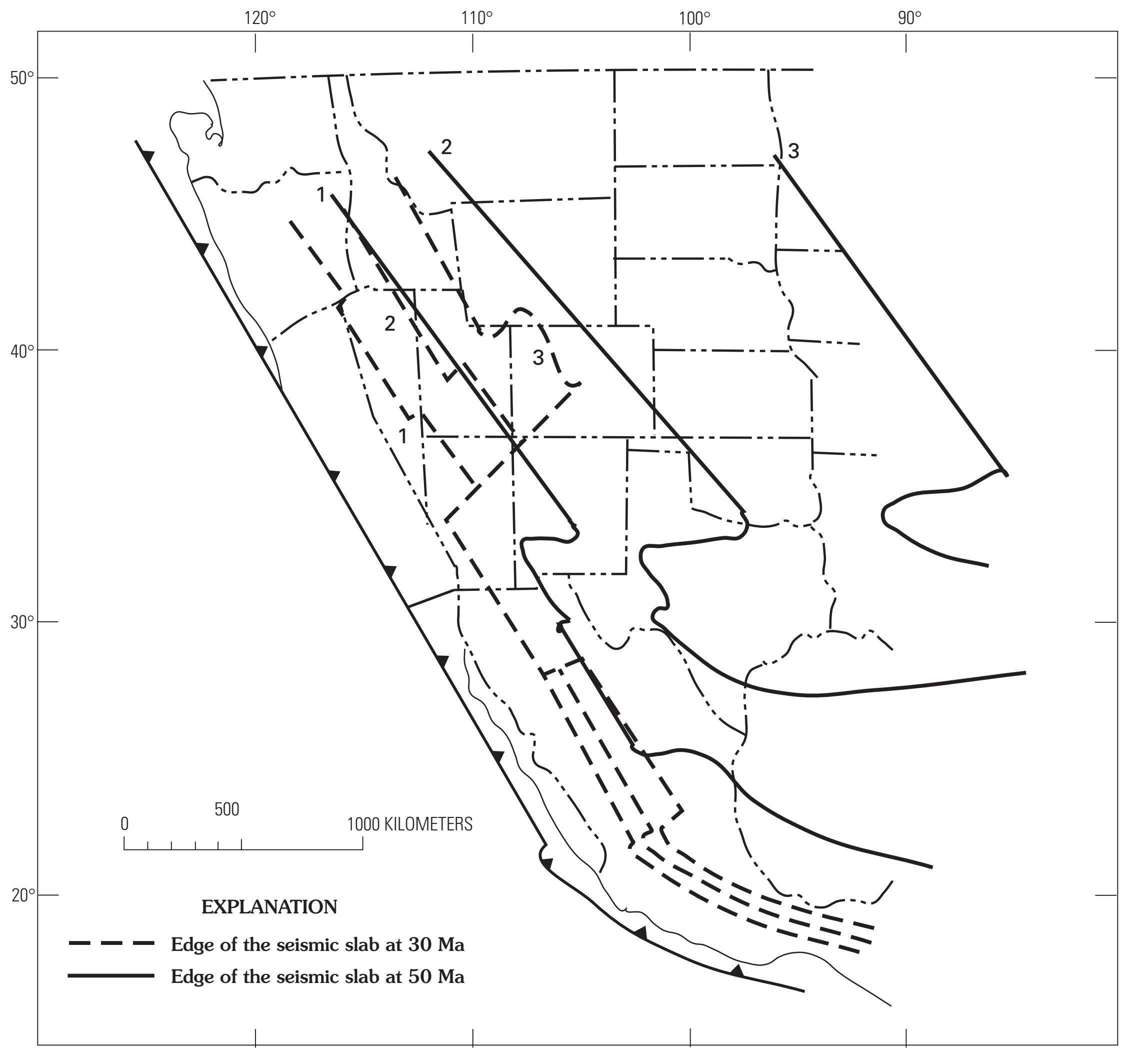

Figure 9. Plate-tectonic reconstruction of the Western United States during Tertiary time at 50 and 30 Ma. Numbered contours represent estimates for the inland limit of the seismically active slab, based on three different assumptions about how long after subduction a slab of a given age and thickness remains distinct from the overlying asthenosphere. (Estimate 1 is most conservative.) After Severinghaus and Atwater (1990).

caldera complex (Best and others, 1989) and the laccoliths, plotted in figure 5, show large ratios of LILE (large-ion lithophile elements, such as Ba) to HFSE (high-field-strength elements, such as Nb). These high ratios suggest the influence of subducted lithosphere; they are characteristic of arc magmas and are believed to result either from LILE-rich slab-derived fluids that infiltrate the overlying mantle wedge (Tatsumi and others, 1986) or from extensive interactions between basaltic melts and the mantle (Kelemen and others, 1990). In theory, any mantle-derived magma could become depleted in HFSE according to the model of Kelemen and others (1990). However, they note that this process is important only in arc settings. Regardless of how the trace element signatures (fig. 3) were acquired, they seem to be a fundamental characteristic of magmas that are at least partly derived from subducted lithosphere. We recognize that high LILE/HFSE ratios could be stored in mantle lithosphere affected by subduction earlier in its history, as has been inferred by the geochemistry of post-subduction Cenozoic basalts of the Western United States (Kempton and others, 1991). However, we favor the interpretation that magmatism with an arc-like geochemical signature was genetically linked to active subduction beneath North America. Based upon our observations, therefore, we present a model for the tectonic setting of the laccoliths and related rock bodies throughout the region that is consistent with both their geochemistry and their temporal and spatial distributions.

We have reviewed geologic observations which suggest that the crust of the Colorado Plateau may be more mafic than that of surrounding regions. Meta-mafic rocks are stronger than their quartz-rich counterparts (Hacker and Christie, 1990), and therefore the difference in rheological

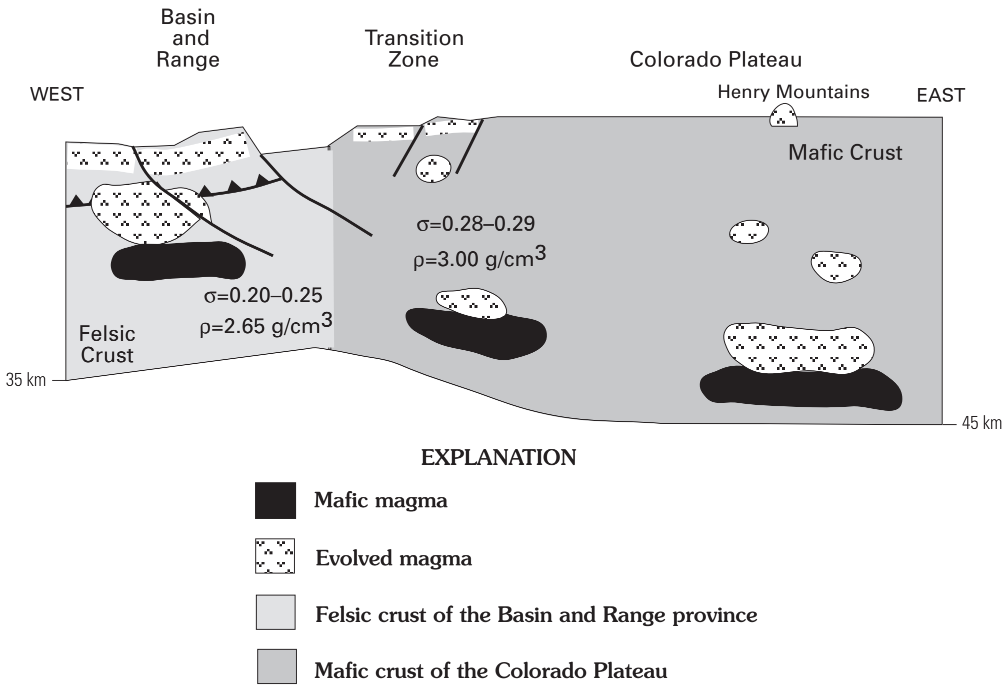

Figure 10. Cartoon diagram illustrating differences in crustal structure, composition, and magma volumes across the Basin and Range province, the transition zone, and the Colorado Plateau interior. Crustal differences between the two provinces are indicated by differences in poisson's ratio σ of the bulk crust (Zandt and others, 1995), and by differences in density (ρ). Crustal thicknesses after Allmendinger and others (1987).

properties between the Colorado Plateau and surrounding regions may be explained by compositional differences. The contrasting physical properties and tectonomagmatic history of the Colorado Plateau and surrounding regions are illustrated in a hypothetical cross section in figure 10.

Best and Christiansen (1991) and Severinghaus and Atwater (1990) suggest that the southwestward sweep of magmatism in the Western United States (fig. 1) was in response to the shortening of the subducting slab (fig. 9) as it adjusted to decreased convergence rates during the Tertiary Period. This resulted in the ingress of hot asthenosphere above the subducted plate, and magmatism was initiated as LILE-rich fluids invaded the growing mantle wedge and reduced solidus temperatures below ambient thermal conditions. The flux of slab-derived fluids accounts for the high Ba/Nb ratios observed throughout the Western United States (fig. 3).

Although the Colorado Plateau laccoliths seem related to the contemporaneous magmatic centers that surround the plateau (Nelson and others, 1992), the volume of magma reaching upper crustal levels at those other centers is several orders of magnitude greater. Best and Christiansen (1991) suggested that Mesozoic shortening surrounding the Colorado Plateau (fig. 10) preconditioned the crust in those regions for magmatic activity. Although shortening will initially depress isotherms, a greater net heat production in thickened radiogenic crust will result in subsequent warming. Overthickening of the crust may also produce gravitational instabilities and crustal extension, further warming the crust. The nearly identical normative (fig. 7) and trace-element (fig. 5) compositions, ages (fig. 1), and volumes of the ash-flow sheets of the Indian Peak and San Juan fields suggest that they were produced in a similar fashion. However, beneath the Colorado Plateau, the presence of substantial mantle-derived magma beneath a thick, unwarmed, and undeformed crust may have contributed to the difference in major-element chemistry (fig. 7) and the large contrast in volume between the Colorado Plateau intrusions and contemporary volcanic fields to the west and east (fig. 10). The model we describe is a consequence of the physical characteristics of the Colorado Plateau and the change in plate motions between Laramide and post-Laramide time. It explains the timing and distribution of magmatism in the Western United States, the subduction chemistry of the magmas, and the differences in igneous volumes between the Colorado Plateau and surrounding regions.

CONCLUSIONS

Plagioclase-hornblende and minor syenite porphyries of the Henry, La Sal, and Abajo Mountains record petrogenetic processes in an unusual geologic setting, the Colorado Plateau interior. Although fractional crystallization could explain the major-element variations and many trace-element variations, radiogenic isotope systematics require open-system interaction of arc-like mantle-derived magmas with mafic but isotopically heterogeneous Proterozoic crust. Plagioclase-hornblende porphyry evolved via assimilation and fractional crystallization in deep-crustal magma chambers until it reached a critical density at which it could overcome the strength of the wall rock and rise to shallow crustal levels. In addition, the plagioclase-hornblende porphyry shows isotopic provinciality, indicating that rocks from each intrusive center were derived from, or interacted with, distinct reservoirs.

Both the plagioclase-hornblende porphyry and the syenite porphyry magma series have trace-element characteristics that indicate that the mantle source was enriched in large-ion lithophile elements relative to high-field-strength elements. This may be a primary source characteristic of the laccoliths and of contemporaneous andesites of the High Plateaus, Great Basin, and San Juan field.

We interpret the magmatism at these centers to be a consequence of subduction and changing plate motions rather than a result of passive hot spot activity. Although the Henry Mountains were far removed from the location of the Tertiary paleo-trench, recent work (Nelson and others, 1992; Nelson and Davidson, 1993) indicates that the Henry, La Sal, and Abajo Mountains were part of a east-west-oriented segment of a late Oligocene arc that extended from the vicinity of Reno, Nev., to the San Juan volcanic field of Colorado. This segment, in turn, was part of a much larger contemporaneous system that extended from Canada to southern Mexico. The arc-like signature of the Colorado Plateau laccoliths and other Oligocene magmatic rocks in the region supports this interpretation. The relatively small volume of the laccoliths suggests that the unusual physical properties of the Colorado Plateau inhibited large volumes of magma from reaching shallow crustal levels.

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REFERENCES CITED

Allen, J.C., and Boettcher, A.L., 1978, Amphiboles in andesite and basalt—II, Stability as a function of P–T–f_{H_2O}–f_{O_2}: American Mineralogist, v. 63, p. 1074–1087.

Allmendinger, R.W., Farmer, Harlow, Hauser, E.C., Sharp, James, von Tish, Douglas, Oliver, Jack, and Kaufman, Sidney, 1986, Phanerozoic tectonics of the Basin and Range–Colorado Plateau transition from COCORP data and geologic data, *in* Barazangi, Muawia, and Brown, L.D., eds., Reflection seismology—The continental crust: American Geophysical Union Geodynamics Series, v. 14, p. 257–268.

Allmendinger, R.W., Hauge, T.A., Hauser, E.C., Potter, C.J., Klemperer, S.L., Nelson, K.D., Kneupfer, P.L.K., and Oliver, J., 1987, Overview of the COCORP 40˚N transect, Western United States—The fabric of an orogenic belt: Geological Society of America Bulletin, v. 98, p. 308–319.

Armstrong, R.L., and Ward, P.L., 1991, Evolving geographic patterns of Cenozoic magmatism in the North American Cordillera—The temporal and spatial association of magmatism and metamorphic core complexes: Journal of Geophysical Research, ser. B, v. 96, p. 13,201–13,224.

Beard, J.S., and Lofgren, G.E., 1991, Dehydration melting and water-saturated melting of basaltic and andesitic greenstones and amphibolites: Journal of Petrology, v. 32, p. 365–401.

Beghoul, Noureddine, and Barazangi, Muawia, 1989, Mapping high P_n velocity beneath the Colorado Plateau constrains uplift models: Journal of Geophysical Research, ser. B, v. 94, p. 7083–7104.

Bennett, V.C., and DePaolo, D.J., 1987, Proterozoic crustal history of the western United States as determined by neodymium isotopic mapping: Geological Society of America Bulletin, v. 99, p. 674–685.

Best, M.G., 1988, Early Miocene change in direction of least principal stress, Southwestern United States—Conflicting inferences from dikes and metamorphic core-detachment fault terranes: Tectonics, v. 7, p. 249–259.

Best, M.G., and Christiansen, E.H., 1991, Limited extension during peak Tertiary volcanism, Great Basin of Nevada and Utah: Journal of Geophysical Research, ser. B, v. 13, p. 13,509–13,528.

Best, M.G., Christiansen, E.H., and Blank, R.H., Jr., 1989, Oligocene caldera complex and calc-alkaline tuffs and lavas of the Indian Peak volcanic field, Nevada and Utah: Geological Society of America Bulletin, v. 101, p. 1076–1090.

Bird, Peter, 1988, Formation of the Rocky Mountains, western United States—A continuum computer model: Science, v. 239, p. 1501–1507.

Boardman S.J., and Condie, K.C., 1986, Early Proterozoic bimodal volcanic rocks in central Colorado, U.S.A., part II—Geochemistry, petrogenesis and tectonic setting: Precambrian Research, v. 34, p. 37–68.

Bowring, S.A., and Karlstrom, K.E., 1990, Growth, stabilization, and reactivation of Proterozoic lithosphere in the Southwestern United States: Geology, v. 18, p. 1203–1206.

Burke, D.B., and McKee, E.H., 1979, Mid-Cenozoic volcano-tectonic troughs in central Nevada: Geological Society of America Bulletin, v. 90, p. 181–184.

Colucci, M.T., Dungan, M.A., Ferguson, K.M., Lipman, P.W., and Moorbath, Stephen, 1991, Precaldera lavas of the southeast San Juan volcanic field—Parent magmas and crustal interactions: Journal of Geophysical Research, ser. B, v. 96, p. 13,413–13,434.

Condie, K.C., 1978, Geochemistry of Proterozoic granitic plutons from New Mexico, U.S.A.: Chemical Geology, v. 21, p. 131–149.

———1982, Plate tectonics model for Proterozoic continental accretion in the Southwestern United States: Geology, v. 10, p. 37–42.

Cross, T.A., and Pilger, R.H., 1978, Constraints on absolute motion and plate interaction inferred from Cenozoic igneous activity in the Western United States: American Journal of Science, v. 278, p. 865–902.

DePaolo, D.J., 1981, Trace element and isotopic effects of combined wallrock assimilation and fractional crystallization: Earth and Planetary Science Letters, v. 53, p. 189–202.

Engel, Celeste, 1959, Igneous rocks and constituent hornblendes of the Henry Mountains, Utah: Geological Society of America Bulletin, v. 70, p. 961–980.

Fitton, J.G., James, Dodie, Kempton, P.D., Ormerod, D.S., and Leeman, W.P., 1988, The role of lithospheric mantle in the generation of late Cenozoic basic magmas in the Western United States, *in* Menzies, M.A., and Cox, K.G., eds, Oceanic and continental lithosphere—Similarities and differences**:** Journal of Petrology, 1988, p. 331–349.

Fountain, D.M., and Christiansen, N.I., 1989, Composition of the continental crust and upper mantle—A review, *in* Pakiser, L.C., and Mooney, W.D., eds., Geophysical framework of the continental United States: Geological Society of America Memoir 172, p. 711–742.

Gill, J.B., 1981, Orogenic andesites and plate tectonics: New York, Springer Verlag, 390 p.

Glazner, A.F., and Bartley, J.M., 1984, Timing and tectonic setting of Tertiary low-angle normal faulting and associated magmatism in the Southwestern United States: Tectonics, v. 3, p. 385–396.

Hacker, B.R., and Christie, J.M., 1990, Brittle/ductile and plastic/cataclastic transitions in experimentally deformed and metamorphosed amphibolite, *in* Duba, A.G., Durham, W.B., Handin, J.W., and Wang, H.F., eds., The brittle-ductile transition in rocks: Geophysical Monograph 56, p. 127–147.

Hamilton, W.B., 1988, Laramide crustal shortening, *in* Schmidt, C.J., and Perry, W.J., eds., Interaction of the Rocky Mountain foreland and the Cordilleran thrust belt: Geological Society of America Memoir 171, p. 27–39.

Helz, R.T., 1976, Phase relations of basalts in their melting ranges at P_{H_2O} = 5 kb—Part II, Melt compositions: Journal of Petrology, v. 17, p. 139–193.

Herzberg, C.T., 1987, Magma density at high pressure—Part 2, A test of the olivine flotation hypothesis, *in* Mysen, B.O., ed., Magmatic processes—Physicochemical principles: Geochemical Society Special Publication 1, p. 47–58.

Hunt, C.B., 1953, Geology and geography of the Henry Mountains region, Utah: U.S. Geological Survey Professional Paper 228, 234 p.

______1958, Structural and igneous geology of the La Sal Mountains, Utah: U.S. Geological Survey Professional Paper 294–I, p. 305–394.

Hunt, G.L., 1988, Petrology of the Mt. Pennell central stock, Henry Mountains, Utah: Brigham Young University Geology Studies, v. 35, p. 81–100.

Irwin, T.D., 1973, The petrologic evolution of the North Mountains stock, La Sal Mountains, Utah: Tucson, Ariz., University of Arizona, M.S. thesis, 71 p.

Jackson, M.D., and Pollard, D.D., 1988, The laccolith-stock controversy—New results from the southern Henry Mountains, Utah: Geological Society of America Bulletin, v. 100, p. 117–139.

Johnson, C.M., 1991, Large-scale crust formation and lithosphere modification beneath middle to late Cenozoic calderas and volcanic fields, western North America: Journal of Geophysical Research, ser. B, v. 96, p. 13,485–13,507.

Johnson, C.M., and Fridrich, C.J., 1990, Non-monotonic chemical and O, Sr, Nd, and Pb isotope zonations and heterogeneities in the mafic- to silicic-composition magma chamber of the Grizzly Peak Tuff, Colorado: Contributions to Mineralogy and Petrology, v. 105, p. 677–690.

Johnson, C.M., Lipman, P.W., and Czamanske, G.K., 1990, H, O, Sr, Nd, and Pb isotope geochemistry of the Latir volcanic field and cogenetic intrusions, New Mexico, and relations between evolution of a continental magmatic center and modifications of the lithosphere: Contributions to Mineralogy and Petrology, v, 104, p. 99–124.

Karlstrom, K.E., Bowring, S.A., and Conway, C.M., 1987, Tectonic significance of an Early Proterozoic two-province boundary in central Arizona: Geological Society of America Bulletin, v. 99, p. 529–538.

Kelemen, P.B., Johnson, K.T.M., Kinzler, R.J., and Irving, A.J., 1990, High-field-strength element depletions in arc basalts due to mantle-magma interaction: Nature, v. 345, p. 521–524.

Kempton, P.D., Fitton, J.G., Hawkesworth, C.J., and Ormerod, D.S., 1991, Isotopic and trace element constraints on the composition and evolution of the lithosphere beneath the southwestern United States: Journal of Geophysical Research, ser. B, v. 96, p. 13713–13735.

Knoper, M.W., and Condie, K.C., 1988, Geochemistry and petrogenesis of early Proterozoic amphibolites, west-central Colorado: Chemical Geology, v. 67, p. 209–225.

Le Bas, M.J., Le Maitre, R.W., Streckeisen, A., and Zanettin, B.A., 1986, A chemical classification of volcanic rocks based on the total alkali-silica diagram: Journal of Petrology, v. 27, p. 745–750.

Lipman, P.W., Doe, B.R., Hedge, C.E., and Steven, T.A., 1978, Petrologic evolution of the San Juan volcanic field, southwestern Colorado—Pb and Sr isotope evidence: Geological Society of America Bulletin, v. 89, p. 59–82.

Lipman, P.W., and Glazner, A.F., 1991, Introduction to middle Tertiary Cordilleran volcanism—Magma sources and relation to regional tectonics: Journal of Geophysical Research, ser. B, v. 96, p. 13193–13199.

Lucchitta, Ivo, 1979, Late Cenozoic uplift of the southwestern Colorado Plateau and adjacent lower Colorado River region: Tectonophysics, v. 61, p. 63–95.

Mattox, S.R., 1991, Petrology, age, geochemistry and correlation of the Tertiary volcanic rocks of the Awapa Plateau, Garfield, Piute, and Wayne Counties, Utah: Utah Geological Survey Miscellaneous Publication 91–5, 46 p.

McGetchin, T.R., and Silver, L.T., 1972, A crustal-upper-mantle model for the Colorado Plateau based on observations of crystalline rock fragments in the Moses Rock dike: Journal of Geophysical Research, v. 77, p. 7022–7037.

McKay, G.A., 1989, Partitioning of rare earth elements between major silicate minerals and basaltic melts, *in* Lipin, B.R., and McKay, G.A., eds. Geochemistry and mineralogy of the rare earth elements: Mineralogical Society of America Reviews in Mineralogy v. 21, p. 45–78.

Nelson, B.K., and DePaolo, D.J., 1984, 1700-Myr greenstone volcanic successions in southwestern North America and isotopic evolution of Proterozoic mantle: Nature, v. 312, p, 143–146.

———1985, Rapid production of continental crust 1.7 to 1.9 b.y. ago—Nd isotopic evidence from the basement of the North American mid-continent: Geological Society of America Bulletin, v. 96, p. 746–754.

Nelson, S.T., 1991, Mid-Tertiary magmatism of the Colorado Plateau—The Henry and La Sal Mountains, Utah: Los Angeles, University of California, Ph.D. thesis, 318 p.

Nelson, S.T., and Davidson, J.P., 1993, Interactions between mantle-derived magmas and mafic crust, Henry Mountains, Utah: Journal of Geophysical Research, ser. B, v. 98, p. 1837–1852.

Nelson, S.T., Davidson, J.P., and Sullivan, K.R., 1992, New age determinations of central Colorado Plateau laccoliths, Utah—Recognizing disturbed K-Ar systematics and re-evaluating tectonomagmatic relationships: Geological Society of America Bulletin, v. 104, p. 1547–1560.

O'Hara, M.H., 1968, The bearing of phase equilibria studies in synthetic and natural systems on the origin and evolution of basic and ultrabasic rocks: Earth Science Reviews, v. 4, p. 69–133.

Ormerod, D.S., Hawkesworth, C.J., Rogers, N.W., Leeman, W.P., and Menzies, M.A., 1988, Tectonic and magmatic transitions in the western Great Basin, USA: Nature, v. 333, p. 349–353.

Perry, F.V., DePaolo, D.J., and Baldridge, W.S., 1993, Neodymium isotopic evidence for decreasing crustal contributions to Cenozoic ignimbrites of the Western United States—Implications for the thermal evolution of the Cordilleran crust: Geological Society of America Bulletin, v. 105, p. 872–882.

Robertson, J.M., and Condie, K.C., 1989, Geology and geochemistry of early Proterozoic volcanic and subvolcanic rocks of the Pecos greenstone belt, Sangre de Cristo Mountains, New Mexico, *in* Grambling, J.A., and Tewksbury, B.J., eds., Proterozoic geology of the Southern Rocky Mountains: Geological Society of America Special Paper 235, p. 119–146.

Rushmer, Tracy, 1991, Partial melting of two amphibolites—Contrasting experimental results under fluid absent conditions: Contributions to Mineralogy and Petrology, v. 107, p. 41–59.

Severinghaus, Jeff and Atwater, Tanya, 1990, Cenozoic geometry and thermal state of the subducting slabs beneath Western North America, *in* Wernicke, B.P., ed., Basin and Range extensional tectonics near the latitude of Las Vegas, Nevada: Geological Society of America Memoir 176, p. 1–22.

Smith, R.B., Nagy, W.C., Julander, K.A., Viveros, J.J., Barker, C.A., and Gants, D.G., 1989, Geophysical and tectonic framework of the eastern Basin and Range–Colorado Plateau–Rocky Mountain transition, *in* Pakiser, L.C., and Mooney, W.D., eds., Geophysical framework of the continental United States: Geological Society of America Memoir 172, p. 205–233.

Sullivan, K.R., Kowallis, B.J., and Mehnert, H.H., 1991, Isotopic ages of igneous intrusions in southeastern Utah: evidence for a mid-Cenozoic Reno–San Juan magmatic zone: Brigham Young University Geology Studies, v. 37, p. 139–144.

Sun, S.S., 1980, Lead isotopic study of young volcanic rocks from mid-ocean ridges, ocean islands, and island arcs: Philosophical Transactions of the Royal Society of London, v. A27, p. 409–445.

Tatsumi, Y., Hamilton, D.L., and Nesbitt, R.W., 1986, Chemical characteristics of fluid phase released from a subducted lithosphere and origin of arc magmas—Evidence from high-pressure experiments and natural rocks: Journal of Volcanology and Geothermal Research, v. 29, 293–309.

Taylor, S.R., and McLennan, S.M., 1985, The continental crust—Its composition and evolution—An examination of the geochemical record preserved in sedimentary rocks: Oxford, Blackwell Scientific, 312 p.

Thompson, G.A., and Zoback, M.L., 1979, Regional geophysics of the Colorado Plateau: Tectonophysics, v. 61, p. 149–181.

Weaver, B.L., and Tarney, John, 1984, Empirical approach to estimating the composition of the continental crust: Nature, v. 310, p. 575–577.

Witkind, I.J., 1964, Geology of the Abajo Mountains area, San Juan County, Utah: U.S. Geological Survey Professional Paper 453, 110 p.

Wolf, L.W., and Cipar, J.J., 1993, Through thick and thin—A new model for the Colorado Plateau from seismic refraction data from Pacific to Arizona crustal experiment: Journal of Geophysical Research, ser. B, v. 98, p. 19881–19894.

Zandt, G., Myers, S.C., and Wallace, T.C., 1995, Crust and mantle structure across the Basin and Range–Colorado Plateau boundary at 37° N. latitude and implications for Cenozoic extensional mechanism: Journal of Geophysical Research, ser. B, v. 100, P. 10529–10548.

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